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The Behavior of Unsteady Thermocapillary Flows

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Surface-tension-driven flows are of central concern to the NASA microgravity fluid dynamics program because they can be the dominant flows in many processes used in a microgravity environment. This project has been an investigation of the behavior of the thermocapillary flow of a thin liquid layer contained in three different geometrical containers: a rectangular cavity, a flat annular cavity, and a cylindrical cavity. In this work, we used asymptotic methods to derive nonlinear evolution equations and boundary conditions for the thermocapillary flows in these geometries. From the numerical solution of these equations, we determined the possible flows, analyzed their stability, and studied the effect of the various system parameters, the effect of interfacial deformation, and the effect of the ends on the flow.

Summary of Results

Steady, two-dimensional flow states in a thin liquid layer contained in a finite rectangular cavity have been found in terms of the free-surface deformation over a finite range of capillary numbers. This range is bounded from above by a limit point value of the capillary number. Below this value, two solution branches occur: a high-deformation branch; and a low-deformation branch. The high-deformation solution branch is unstable and the layer tends toward either the stable, lower-branch solution, or to film rupture. Above the limit-point value, no steady-state flows exist. The layer seems to progress towards a ruptured-film state at the hot end of the film.

The influence of inertia in the liquid layer was examine by allowing for a flow with a large Reynolds number. The resulting leading-order momentum equation was solved approximately using an integral technique. A parabolic longitudinal velocity was assumed, it was substituted into the momentum equation, and the result was averaged over the thickness of the layer. The resulting momentum equation, together with a mass conservation equation was solved using the same pseudo-spectral techniques used for the viscous-dominated case. The results show that the effect of inertia in the liquid is to reduce the free-surface deformation for a given capillary number and to increase the value of the limit-point capillary number. The upper-branch solution is still unstable and the lower-branch solution is stable. However, at low capillary numbers, the preferred disturbance mode for the lower branch is oscillatory when inertia is included. We have shown that for small enough capillary numbers, the free surface behaves like a damped vibrating beam.

Steady, axisymmetric flow states have also been found in terms of free-surface deformation over a finite range of capillary numbers for flows occurring in a wide, flat annular cavity with a flat free-surface, and in a shallow cylindrical cavity with a cylindrical free-surface. The basic flow states in the annular cavity are similar to the rectangular cavity discussed earlier. The effect of azimuthal curvature is to destabilize the film when the inner radius of the film is large. This means that the limit-point capillary number is decreased. However, when the inner radius is small enough, the film is stabilized significantly. Near the point where the inner radius goes to zero, the film is completely stabilized . In this situation, a steady-state film profile is possible for all values of the capillary number. The limit-point capillary number goes off to infinity.

In a shallow cylindrical cavity, the inherent cylindrical curvature of the free surface always has a destabilizing effect on the film flow. The extra destabilization is due to a Rayleigh capillary instability associated with this geometry.

Conclusions

We have found that it is possible to have steady thermocapillary flows in any of these three systems provided the liquid layer is not too thin or the surface tension is not too small. If these conditions are not met, then no steady solutions are possible and the film thins and approaches a condition of rupture near the hot end.

Future work on these problems will include the effect of liquid inertia in the calculations for the cylindrical cavity. The stabilization effect of inertia may offset the destabilization effect inherent in the cylindrical geometry and result in a stable film flow on the cylinder. This type of behavior could be very significant in terms of understanding the stability of thermocapillary flow in liquid bridges and in the float-zone crystal growth process.

Publications and Presentations

Refereed Publications:

Vrane, D. R. & Smith, M. K., "Free-surface instabilities in confined, low Prandtl number, thermocapillary-driven flows. Part 1. Viscous and inertial effects," submitted to JFM.

Vrane, D. R. & Smith, M. K., "Free-surface instabilities in confined, low Prandtl number, thermocapillary-driven flows. Part 2. The influence of domain curvature," submitted to JFM.

Conference Presentations:

Vrane, D. R. & Smith, M. K., "The Behavior of Unsteady Thermocapillary Flows," Second Microgravity Fluid Physics Conference, Cleveland, OH, June 21-23, 1994.

Vrane, D. R. & Smith, M. K., "The Influence of Domain Curvature on the Stability of Viscously-Dominated Thermocapillary Flows," AMS-IMS-SIAM Joint Summer Research Conference on 'Analysis of Multi-Fluid Flows and Interfacial Instabilities', Seattle, WA, July 23-27, 1995.

Vrane, D. R. & Smith, M. K., "The High Capillary Number Behavior of a Viscously-Dominated, Thermocapillary-Driven Flow in a Two-Dimensional Rectangular Cavity," Forty-Seventh Meeting of the American Physical Society - Division of Fluid Dynamics, Atlanta, GA, November 20-22, 1994.

Vrane, D. R. & Smith, M. K., "The Influence of Domain Curvature on the Stability of Viscously-Dominated Thermocapillary Flows," Forty-Eighth Meeting of the American Physical Society - Division of Fluid Dynamics, Irvine, CA, November 19-21, 1995.

Vrane, D. R. & Smith, M. K., "Inertial Stabilization of Capillary Break-up in a Thermocapillary-Driven Cylindrical Cavity," Forty-Ninth Meeting of the American Physical Society - Division of Fluid Dynamics, Syracuse, NY, November 24-26, 1996.

Dissertation:

Vrane, D. R., "The stability of thermocapillary-driven flows in finite regimes," Georgia Institute of Technology, 1996.

Invited Seminars:

Smith, M. K., "Confined Liquid Films Driven by Surface-Tension Gradients," Department of Chemical Engineering, University of Notre Dame, South Bend, IN, October 25, 1996.